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ADVANCED AND INNOVATIVE WIND ENERGY CONCEPT DEVELOPMENT: DYNAMIC INDUCER SYSTEM

EXECUTIVE SUMMARY

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ABSTRACT AND OVERVIEW

Innovative concepts are being sought to improve the technical and economic performance of wind energy conversion systems (WECS). One promising technique for improving the cost-effectiveness of WECS is the use of tip vanes. Tip vanes are small airfoils attached approximately at right angles to the rotor tips with their span oriented approximately parallel to the local freestream (Figure 1). The tip vanes serve to increase the capture area and power output of the rotor, and have the potential of high power increases without significant penalties in terms of the size, complexity or cost of the system.

The dynamic inducer system has the capability of achieving about the same augmentation as a static duct, which also augments the mass flow through the actuator. In the present case, the aerodynamic forces on the moving tip vanes induce flow through the rotor and achieve augmentation. Thus, it is referred to as a dynamic inducer. Since it requires considerably less structure, the dynamic inducer has the potential for surpassing the overall efficiency and economic performance of conventional static augmentors.

The cost/benefit advantages of the dynamic inducer include:

- significant power increases,
- simple and compact structure,
- adaptability to conventional rotors, and
- feathering control via tip vanes possible.

For the past three years, AeroVironment Inc. (AV) has been active with the analytical and experimental investigation of the dynamic inducer. This work was originally funded by the U.S. Department of Energy (DOE) and later supported by SERI under Contract No. XH-9-8085-1. The goal of this program was to experimentally substantiate the improved power output of a dynamic inducer system predicted from theory. The specific elements of the program included:

- <u>Task 1 - Analysis</u>. An analytical model was developed with the capability of predicting tip vane performance in viscous rotating flow and for non-synchronous operation. The model was utilized for the development of designs for tip vanes and power blades for wind tunnel tests and field tests.
- <u>Task 2 - Wind Tunnel Test</u>. A scale model of the dynamic inducer was designed, fabricated, and tested in a wind tunnel facility. A new method for calculating wind tunnel corrections for augmented wind turbines was developed. This shows that corrections are very significant. For example, with a blockage of 16%, the corrected power coefficient is about 20% lower than that actually measured.
- <u>Task 3 - Field Test</u>. A full-scale dynamic inducer system was designed, fabricated, and tested on a conventional three-bladed, 3.6-m diameter WECS.

In this program, the performance benefits of the dynamic inducer tip vane system have been experimentally demonstrated for the first time. Tow-tests conducted on a

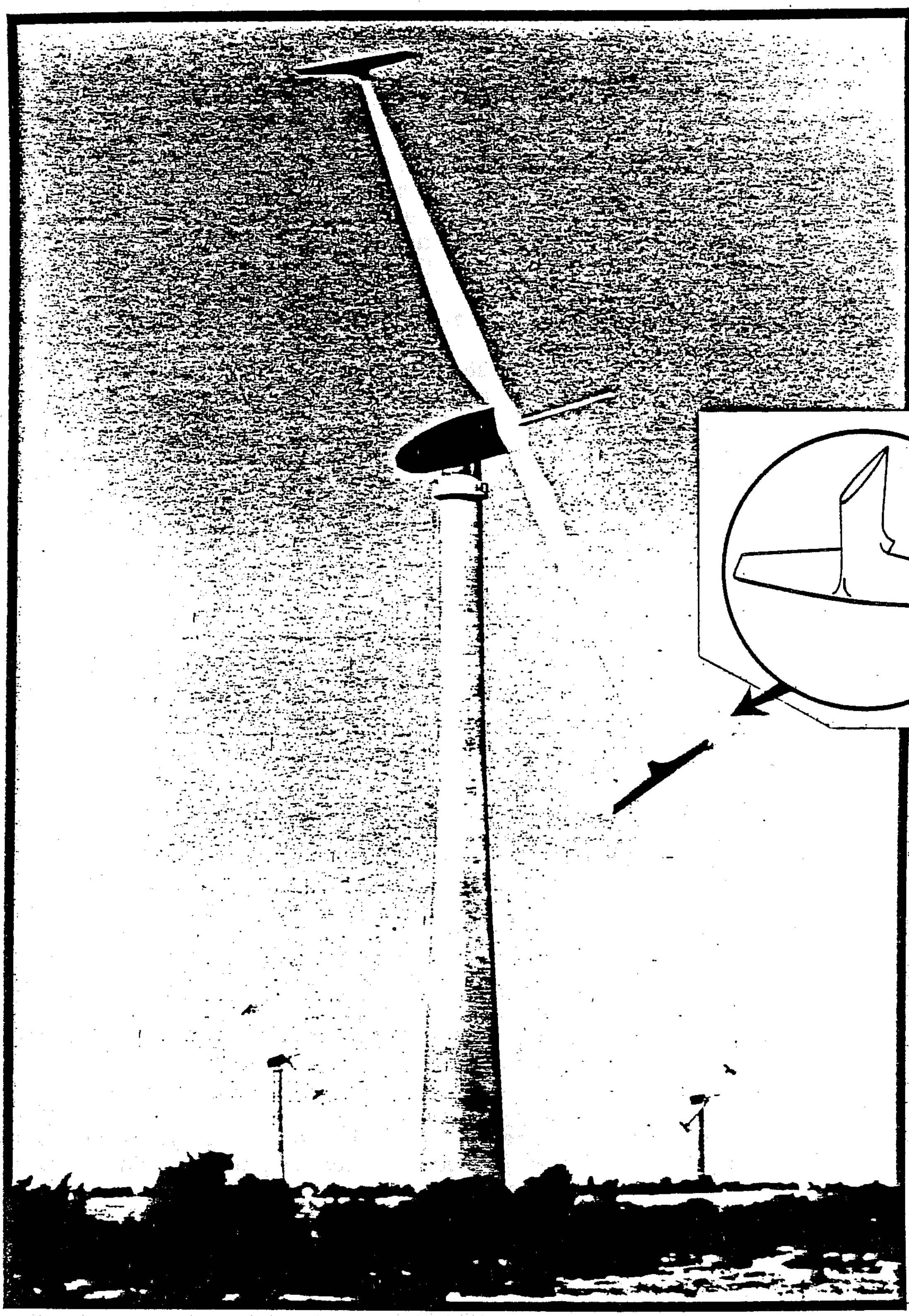

Figure 1. CLUSTER OF DYNAMIC INDUCERS (ADAPTED FROM POSTER SHOWING CONVENTIONAL WECS PUBLISHED BY NATIONAL SWEDISH BOARD OF ENERGY SOURCE DEVELOPMENT)

three-bladed, 3.6-meter diameter rotor have shown that a dynamic inducer can achieve a power coefficient (based upon power blade swept area) of 0.5, which exceeds that of a plain rotor by about 35%. Wind tunnel tests conducted on a one-third scale model of the dynamic inducer achieved a power coefficient of 0.62 which exceeded that of a plain rotor by about 70%. The dynamic inducer substantially improves the performance of conventional rotors and indications are that higher power coefficients can be achieved through additional aerodynamic optimization. A brief discussion of the analytical program, wind tunnel tests, and field tests is given, followed by conclusions and recommendations.

ANALYTICAL PROGRAM

To determine the performance characteristics of the dynamic inducer and to select a suitable design based upon these calculations, an analytical investigation was conducted. To evaluate candidate rotor and tip vane designs, the following criteria were used:

- potential for high augmentation,
- compatibility with available three-bladed, 3.6-m, 1200-watt commercial (Kedco) WECS, and
- ease of fabrication.

An available, non-optimum three-bladed rotor was selected as the baseline system (Figure 2). While it was recognized that higher augmentations are possible with more advanced configurations, such as a two-bladed, low-solidity, high tip speed rotor, it was felt that further optimization of the WECS design could be achieved once the basic operation of the dynamic inducer was demonstrated. Table 1 summarizes the elements of the baseline rotor.

A dynamic inducer system was designed for a conventional commercially available (Kedco 1200) 3.6 m diameter three-bladed rotor using the analysis described in the main report (Lissaman et al., 1980). The general layout of the dynamic inducer system is shown in Figure 3. The system was designed to achieve a power coefficient $C_p = 0.57$ in the freestream at the maximum tip vane lift coefficient, $C_L = 1.2$. This represents a 40% improvement over the performance of the baseline rotor at the nominal feather angle of 12°, as shown in Figure 4. The performance of the tip vanes at lower lift coefficients is also shown.

This level of augmentation is much lower than theoretically possible because the commercially available non-optimum three-bladed rotor system was selected as a power blade system. Higher power augmentations can be achieved with more advanced configurations such as a two-bladed low solidity high tip speed ratio rotor.

WIND TUNNEL TESTS

A one-third scale model of the dynamic inducer system was fabricated. It was tested in the Caltech 10-foot diameter wind tunnel. The metric system consisted of a

One-Third Scale Model of Kedco 1200-watt Turbine

Design Tip Speed Ratio	4.5
Solidity	13%
Profile	Wortman FX60-126 (root), FX61-184 (tip)
Twist	9-1/2°

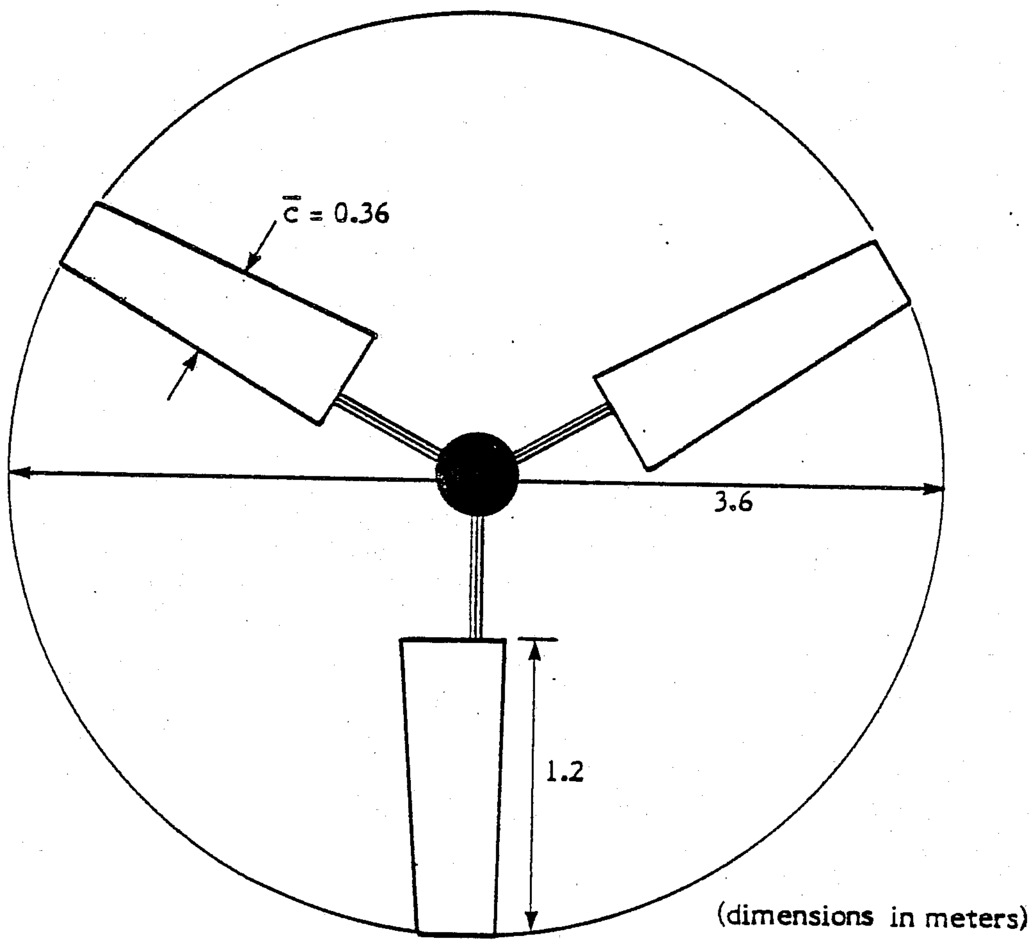

Figure 2. BASELINE ROTOR SYSTEM SELECTED FOR PROGRAM

Table 1. SELECTED DESIGN PARAMETERS FOR DYNAMIC INDUCER

Parameter	Criteria	Result
BASELINE ROTOR		
Design tip speed ratio	Given	X = 4
Solidity	Given	13%
Profile	Given	FX61-126, 184
Twist	Given	9°
Number of blades	Given	3
TIPVANE SYSTEM		
Span	System synchronous at X = 1-3	b/R = .5 to .7
Chord	Desired power augmentation ~ 40%	$\bar{c}/R = .12$
Profile	High lift-to-drag ratio	NACA 4415
Aspect ratio	Minimize induced drag	4
Taper	Minimize induced drag	3:2
Twist	Simple fabrication	No twist
Power blade/tip vane junction	Minimize parasite drag	Fairing made for junction
Tip modifications	Minimize asymmetric tip suction	Tip of upwind tip raked 30°; Hoerner tip and a rounded tip used on upwind and downwind tips, respectively

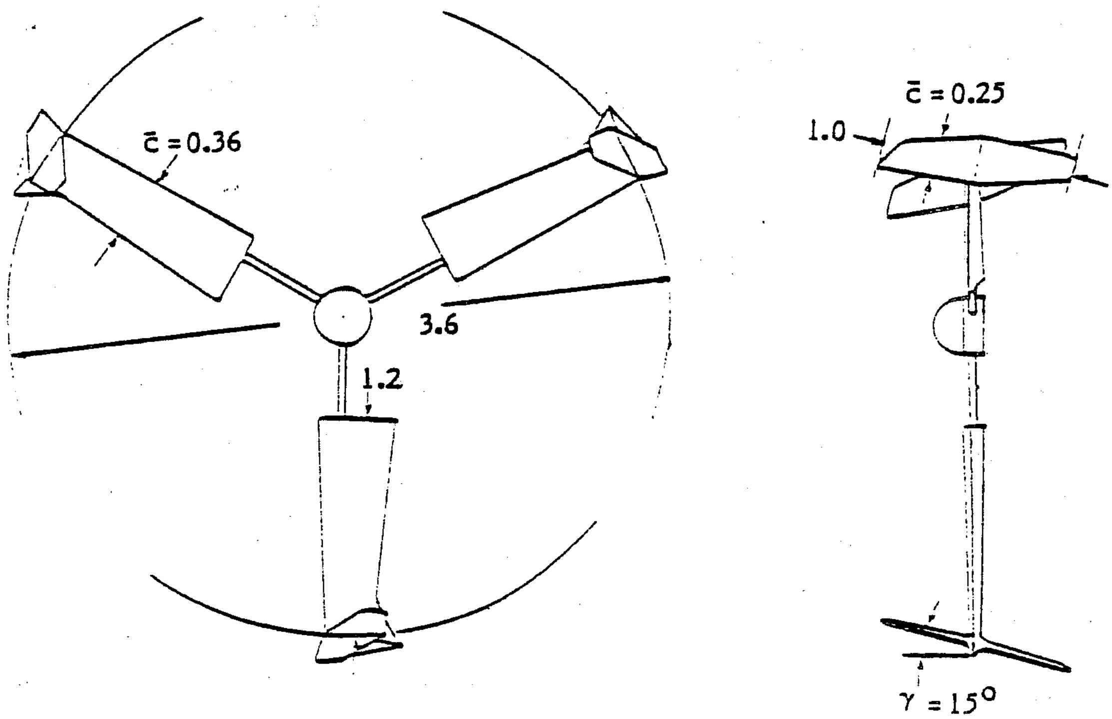

Figure 3. VIEWS OF FULL-SCALE DYNAMIC INDUCER (DIMENSIONS IN METERS)

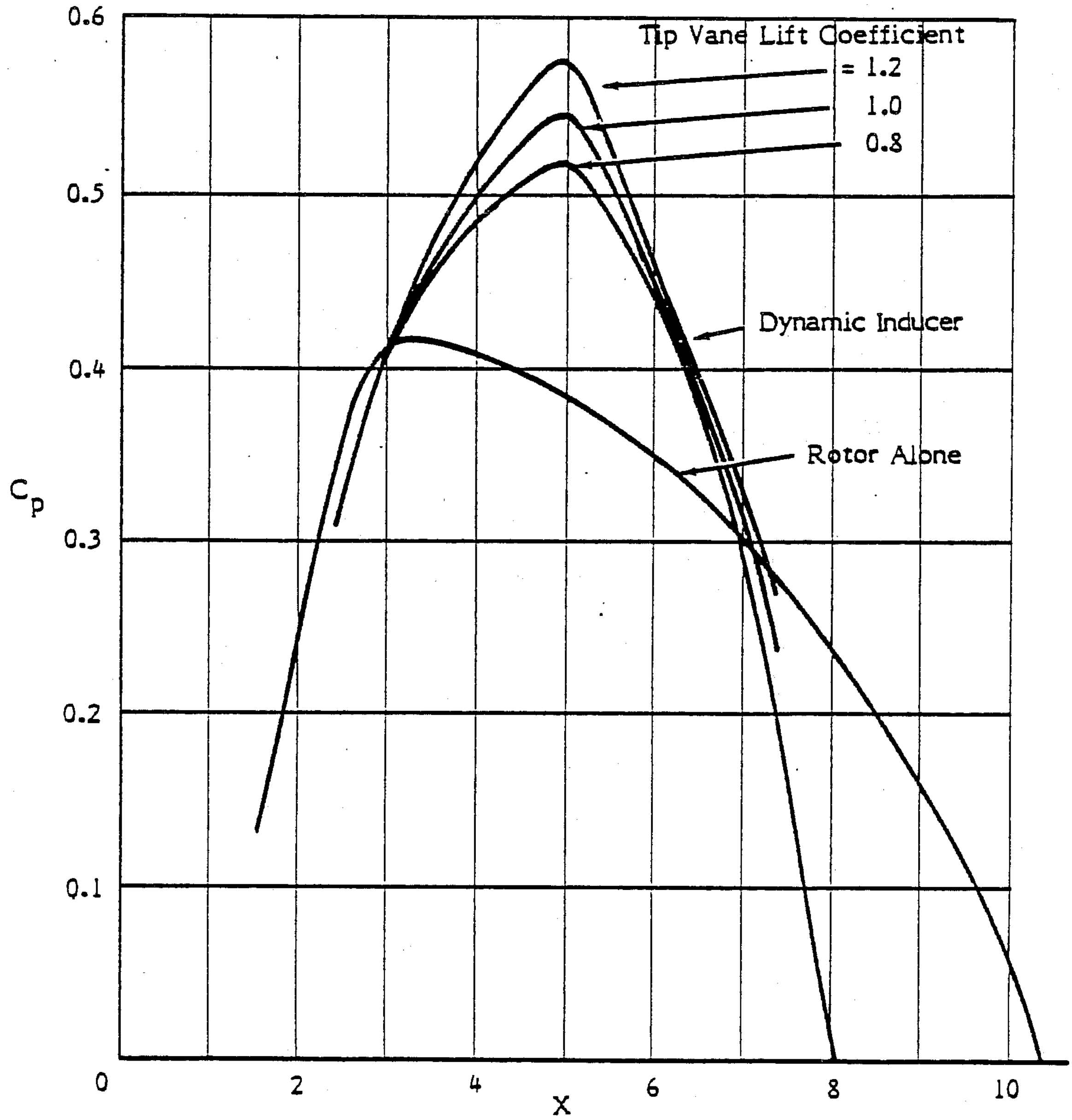

Figure 4. THEORETICAL POWER COEFFICIENTS FOR ROTOR ALONE AND DYNAMIC INDUCER

3-horsepower D.C. motor, tachometer and in-line shaft mounted torque and thrust transducers as shown in Figure 5. The accuracy of the RPM, torque and thrust monitoring instruments was within 1, 2, and 5% respectively. The D.C. motor was equipped with a regenerative drive and feedback controller enabling it to maintain a specified RPM under an arbitrary positive or negative load. Under negative loads, the motor functioned as a brake (generator) feeding power back into the line. It was expected that the inducer system may require power for spin-up at some settings, but sufficient starting torque was available from the dynamic inducer so that the motor actually operated in the generator mode for all of the test conditions.

The thrust and torque coefficients were measured over a range of tip speed ratios from 2 to 8 for a total of 51 different model configurations, including variations in blade feather angle and tip vane geometry. The majority of the tests were conducted at a freestream velocity of 10 m/s corresponding to a Reynolds number of 640,000 at a nominal tip speed ratio of 4 for the tip chord. The freestream velocity was reduced to 8 m/s at tip speed ratios above 6 to reduce the blade loads. The reference freestream velocity was measured to within 1% by the pitot-static system installed in the wind tunnel.

The tests were conducted in the following manner: 1) the tunnel was brought up to speed, 2) the rotor RPM was set corresponding to a specified tip speed ratio, 3) the tunnel velocity was brought to equilibrium, and 4) the RPM, thrust and torque values were recorded from the digital readouts over a 10-second averaging period. The repeatability of the measurements were within the accuracy of the instruments.

The power coefficients of the dynamic inducer, normalized by the maximum power coefficient of the rotor alone, are plotted against the tip speed ratio, X, in Figure 6, using the theoretical predictions and observed and corrected wind tunnel measurements. The wind tunnel correction factors were derived on the basis of a new theory described in the main text. The wind tunnel correction factors are shown in Figure 7. At typical operating conditions, $C_L = 1.2$, $X = 4$, so that $C_{TD} = 0.3$. At the highest power coefficient setting, the total thrust coefficient of the system was $C_T \sim 1.2$. Thus, the power coefficient of the dynamic inducer was approximately 20% higher in the wind tunnel than in the freestream. Similarly, about a 20% correction is predicted for the rotor alone configuration ($C_{TD} = 0$) at the highest power coefficient setting.

The results in Figure 6 indicate that the dynamic inducer increases the maximum power coefficient of the rotor on the order of 70%, and reduces the tip speed ratio range of the system somewhat from 2 to 8 to 2 to 5. Comparison of the wind tunnel measurements with the theoretical predictions shows similar trends. However, the theoretical model predicts lower augmentations occurring at higher tip speed ratios. This is believed to stem from simplifications in the model. Additional work is warranted in this area.

FIELD TEST

A field test was conducted to measure the power output of a full-scale dynamic inducer system. The objective of the tow-test was to demonstrate the operation of the dynamic inducer system under realistic conditions.

The model consisted of the 3.6-m diameter commercially available three-bladed Kedco wind turbine fitted with tip vanes approximately 1 m in span and 0.25 m in chord, illustrated earlier in Figure 2. Figure 8 is a photograph of the model mounted on a trailer.

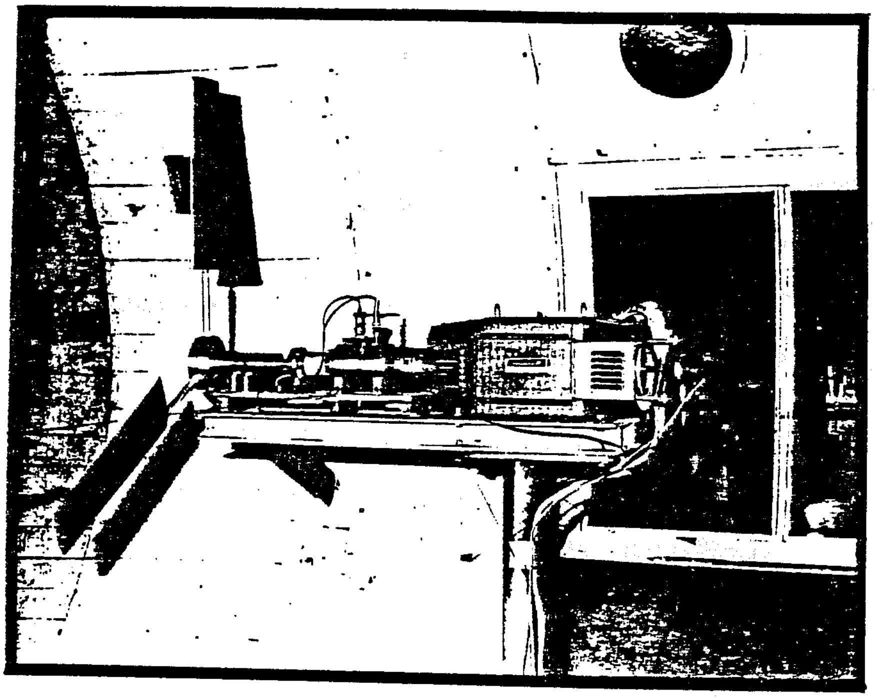

Figure 5. ONE-THIRD SCALE WIND TURBINE MODEL INSTALLED IN 10-FOOT DIAMETER WIND TUNNEL

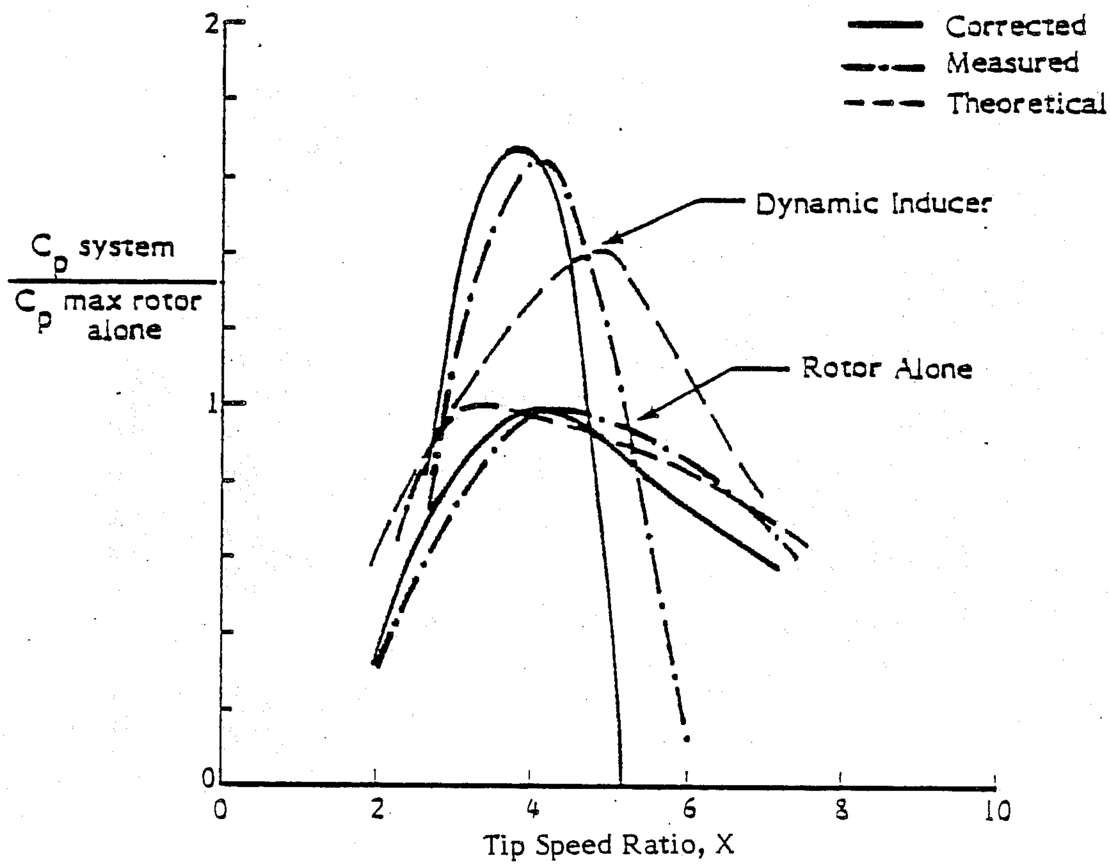

Figure 6. NORMALIZED POWER COEFFICIENTS VERSUS TIP SPEED RATIO FOR ROTOR ALONE AND DYNAMIC INDUCER

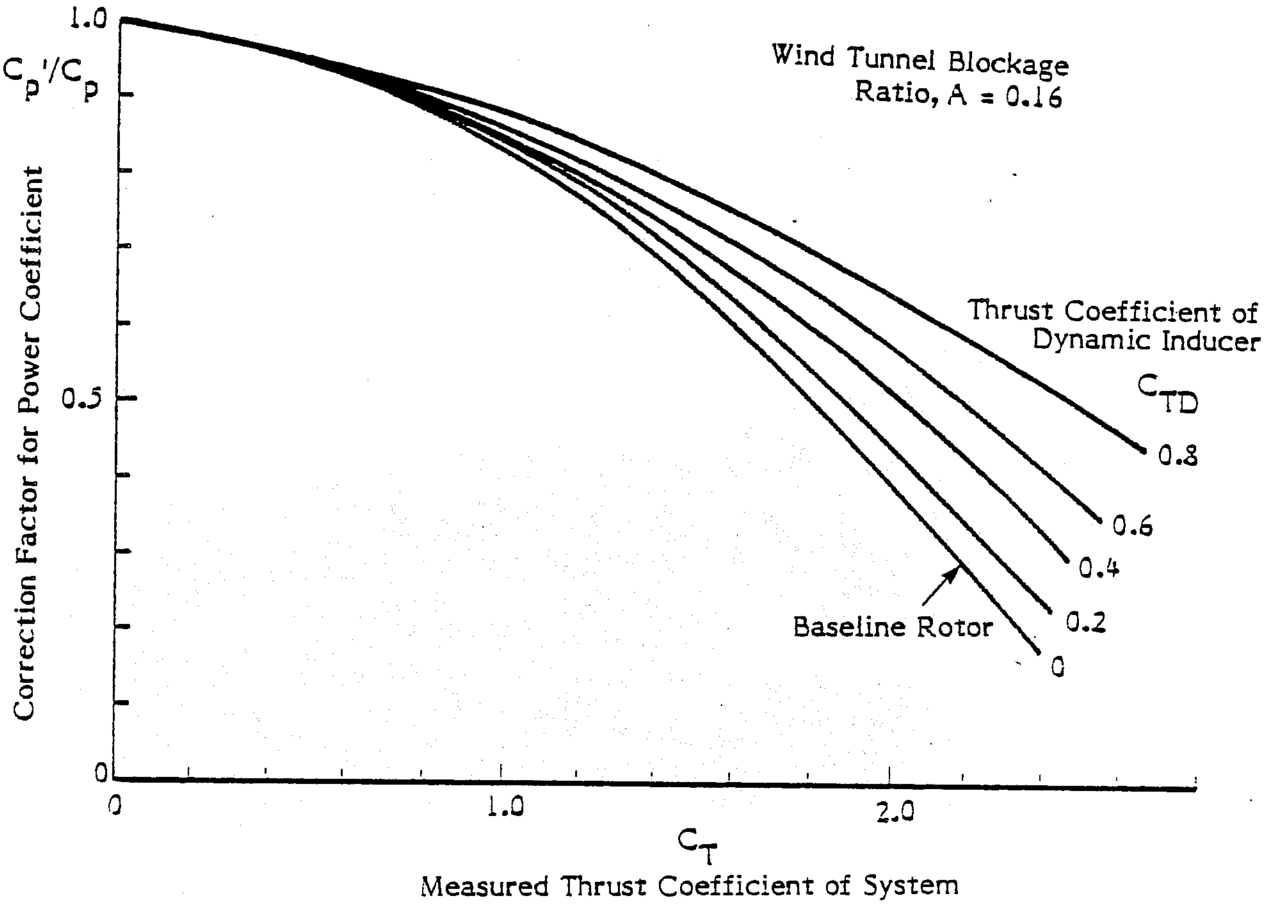

Figure 7. WIND TUNNEL CORRECTION FACTORS FOR DYNAMIC INDUCER

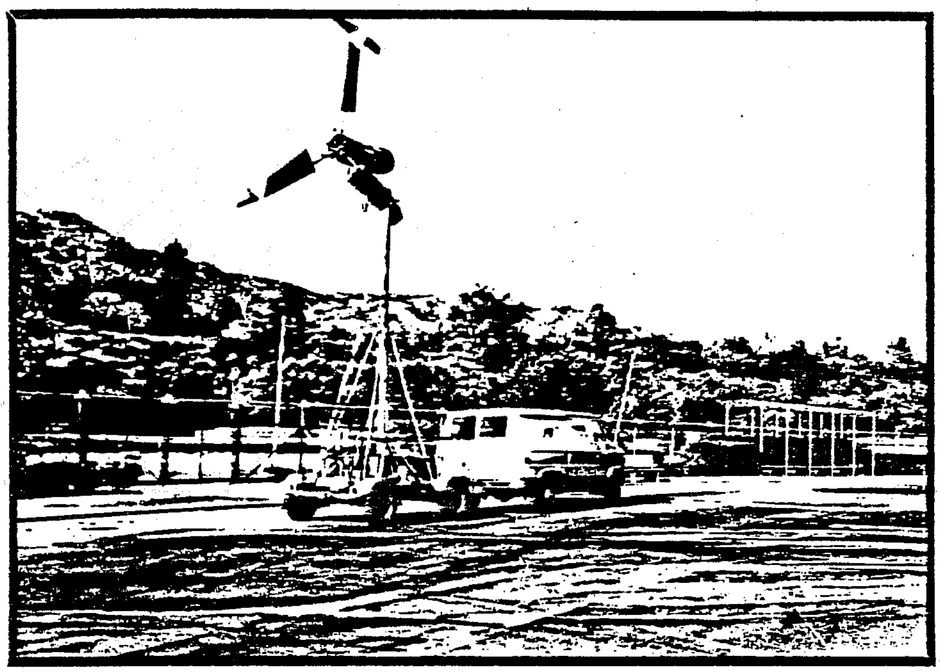

Figure 8. PHOTOGRAPH OF FULL SCALE DYNAMIC INDUCER

A trailer-mounted tower equipped with an electronic system for varying the electrical load on the Kedco wind turbine was utilized for the field tests. The wind speed was measured by a Gill anemometer mounted on a 5-m boom ahead and above the vehicle.

The testing of the full-scale turbine involved towing the trailer at a fixed air speed (6 to 8 m/sec) with the rotor positioned about 7 m above ground. Once the rotor reached a selected operating rpm, the output from the turbine including the rpm, field resistance, output voltage, wind speed, and output current was recorded on a five-channel strip chart recorder. Typically, a 10- to 20-second record was obtained at each blade pitch setting. The runs at each setting were repeated several times and no significant drift, intermittency or scatter was noted.

The tip vane system was tested on the baseline rotor at a fixed yaw, tilt, and angle of attack. Efforts were not made to optimize the orientation of the tip vanes due to budget and time constraints.

Figure 9 shows the comparison of the measurements obtained from the full-scale tow tests with theory and the results from the earlier wind tunnel tests. The results show a 42% higher maximum power coefficient for the full-scale rotor than for the one-third scale wind-tunnel model. Moreover, the design tip speed ratio is 12% higher for the full-scale rotor than for the wind tunnel model. While a slightly higher performance is anticipated for the full-scale rotor due to the higher Reynolds numbers, such a large increase in performance is suspicious. The reason for the mismatch in power coefficient is not clear. A possible explanation may be an inaccuracy in the measurement of the wind speed. The 42% increase in the maximum power coefficient can result from a 12% increase in the freestream velocity. Improper positioning of the reference anemometer in the accelerated flow field of the van used to pull the trailer can account for a 12% increase in velocity. Significantly, a 12% adjustment of the freestream velocity would also lower the design tip speed ratio for the full-scale rotor and match the results obtained in the wind tunnel.

Comparison was made of the results from the present tow-tests with results published earlier (Lissaman and Walker, 1968). The electrical power output of the turbine was identical. However, in the earlier report the power coefficient of the turbine was calculated based on generated electrical power and included all electrical and mechanical losses in the system. In this report, the power coefficient was based on mechanical power measured at the rotor shaft (no mechanical or electrical losses were included) since it was desired to compare the measurements obtained from the field test and wind tunnel test on a common basis. Thus, higher values of power coefficient are predicted than in the earlier report. The observed power coefficient of 0.52 for the baseline turbine is consistent with the earlier measurements when the proper corrections for density and dynamic pressure are used.

Figure 9 shows the power coefficient versus tip speed ratio for the full-scale dynamic inducer. A maximum power coefficient of 0.675 was achieved at a tip speed ratio of 4.0 for a feather angle of $\beta = 10^{\circ}$. The repeatability of the measurements is within about 10%, as shown by the scatter in the data points.

Figure 10 shows a comparison of the performance of the full-scale dynamic inducer with wind tunnel tests and theoretical predictions. The results indicate that the maximum power coefficient of the dynamic inducer is 11% higher for the field tests than for the wind tunnel tests. Comparing the performance of full-scale dynamic inducer with the full-scale rotor, a 30% increase in power coefficient is observed.

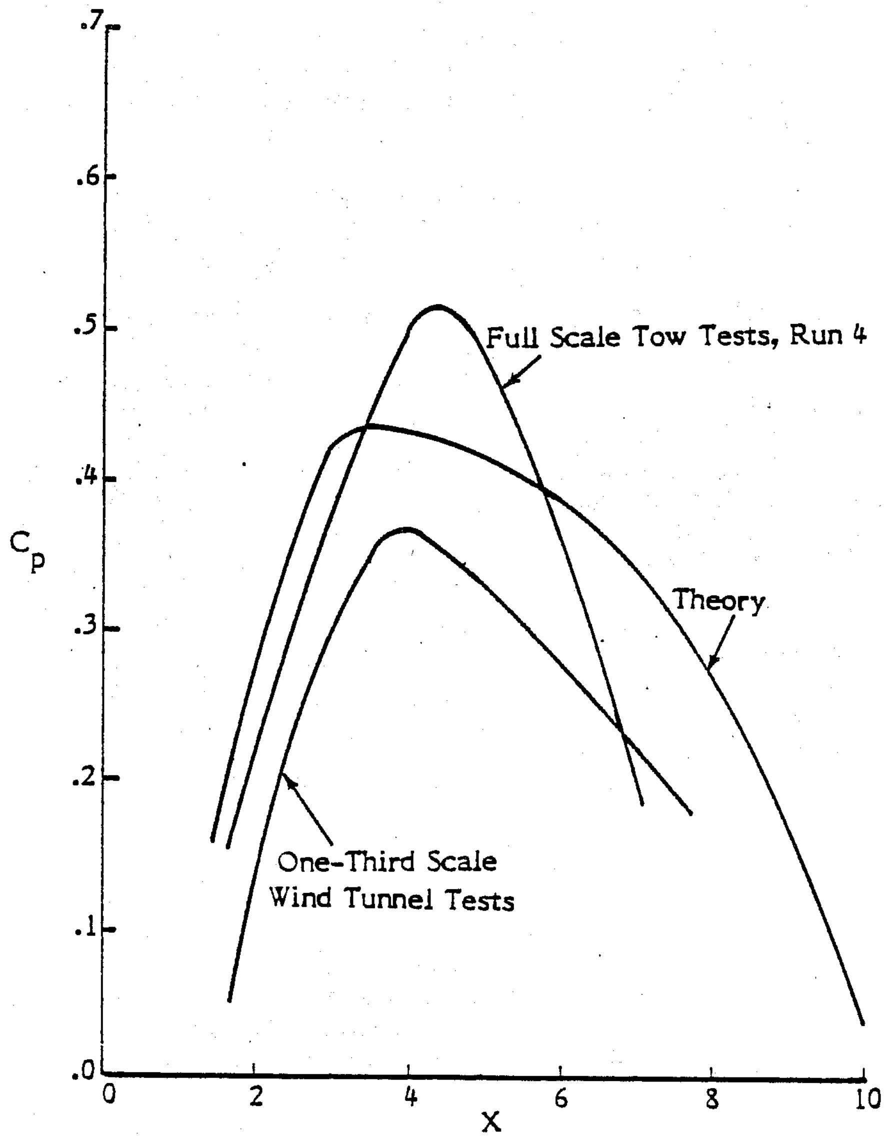

Figure 9. COMPARISON OF POWER COEFFICIENT VERSUS TIP SPEED RATIO OF BASELINE ROTOR OBSERVED DURING TOW TESTS WITH THEORETICAL PREDICTIONS AND WIND TUNNEL MEASUREMENTS

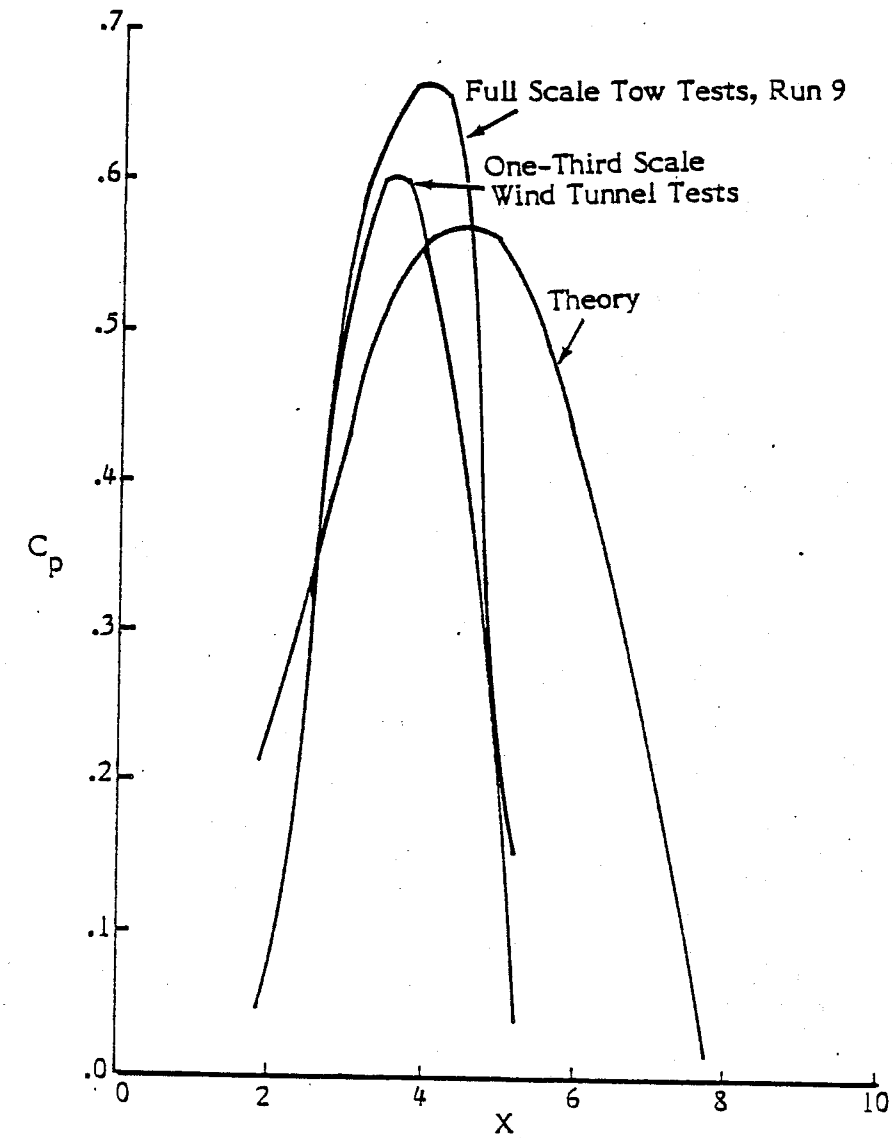

Figure 10. COMPARISON OF DYNAMIC INDUCER POWER COEFFICIENT OBSERVED DURING TOW TESTS WITH THEORETICAL PREDICTIONS AND WIND TUNNEL MEASUREMENTS

CONCLUSIONS AND RECOMMENDATIONS

The conclusions of this effort are:

- the dynamic inducer system can substantially increase the power output of a conventional rotor system,
- wind tunnel corrections are very important for augmented turbine systems, and
- the performance benefits of the dynamic inducer system are likely to be higher for optimized configurations.

The favorable results obtained in this program suggest that the dynamic inducer system can play a major role in future WECS technology.

To demonstrate the technical and economic advantages of the dynamic inducer system, work is recommended in the following areas:

- development of an optimized dynamic inducer system suitable for commercial applications such as a two-bladed high tip speed ratio low solidity WECS,
- evaluation of the potential economic performance of the optimized commercial system, and
- validation of the economic and performance benefits of prototype full-scale dynamic inducer under actual operating conditions.

To develop and refine techniques for testing and evaluating wind turbines, work is recommended in the following areas:

- validation of the wind tunnel correction factors developed for wind turbines by means of a series of controlled wind tunnel tests using closed and open jet tunnels;
- validation of the tow-test procedures for evaluation of turbine performance by conducting tow tests on the same model at different facilities under controlled conditions.